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Introduction

The area of the Upper Rhine between Lake Constance and Basle presents an exceptionally complete record of the climatic oscillations during the Last and Penultimate Glaciations. Three exceedingly rich Magdalenian sites have been found here in association with glacifluvial deposits connected with terraces of the Rhine. Elsewhere the true Magdalenian is almost confined to cave sites. In these it is difficult to obtain a clear climatic succession ; and, in nearly all, impossible to link the archaeological levels with either moraines or loesses. In the present paper we have analysed the terraces and glacifluvial gravel-trains of the Upper Rhine in an attempt to obtain as complete a record as possible of the phases of the Last Glaciation. We have also attempted to determine the position of the Magdalenian within this succession. Our object was to substantiate, modify or disprove, the relative age at present assigned to the Magdalenian : namely, from after the maximum of the second phase of the Last Glaciation to the beginning of the third (see Zeuner, 1946, p. 154). Finally, we deem the present evidence in favour of the solar radiation hypothesis sufficiently cogent to warrant a short inquiry[1] as to what sort of answer an application of the Radiation Curve would yield to the question : what (in thousands of years) was the absolute duration of the Magdalenian ?

The first part of this paper deals with the climatic chronology and is inevitably highly technical. It scrutinizes the evidence for glacial phases and subphases derived from glacifluvial sheets emanating from terminal moraines ; attempts to separate the deposits of the Last Glaciation from those of the Penultimate ; and deduces from the former the number and relative magnitude of the glacial phases of the Last Glaciation.

The second part begins with a summary of the results of the first and can therefore be read independently. It discusses the relation of the Magdalenian sites of the area to certain moraines and their glacifluvial terraces ; deals with the climatic fluctuations experienced by Magdalenian man ; seeks to fix the position of the Magdalenian in the climatic framework provided by the phases of the Last Glaciation. Finally, the consequence of applying the Radiation Curve to the results so obtained, is discussed.

The longitudinal profile of the terraces of the Upper Rhine (fig. 3) is based on over 250 points, a detailed list of which has been deposited in the University of London Institute of Archaeology for reference. The additional cost of printing made it impossible to include this in the present paper.

The Upper Rhine between Lake Constance and Basle forms the frontier between Switzerland and Baden ; or, near Basle, between French Alsace and Baden. The international character of the river introduces a difficulty in regard to map altitudes which is explained in the legend to fig. 3 (folder).

[1] This seemed the more necessary because, apparently, the nature of the results obtainable has been very generally misconceived.

Part I

THE TERRACES OF THE UPPER RHINE

In 1936, Ludwig Erb published an important paper on " The Stratigraphy of the Middle and Upper Pleistocene of South-West Germany and the adjacent Swiss Area " (Erb, 1936). It consists of a critical re-examination of the results of earlier work on the Pleistocene terraces of the Rhine between Basle and Schaffhausen. It was no doubt prompted, if not necessitated, by Erb's extensive field work in mapping the crucial inter-morainic area north-east of Schaffhausen (Erb, 1931). It constitutes a substantial addition to our knowledge of the Alpine glaciations since Great Interglacial times. Its particular importance lies in the fact that it suggests sub-divisions of the two latest Pleistocene glaciations, which are likely to be of more than local interest.

Erb's paper is primarily concerned with the proper grouping of the many marginal, glacifluvial outwash fans and gravel trains of the Schaffhausen area, according as they merge, when traced westwards, with one or other of the river terraces of the upper Rhine. These latter have a gentler gradient, are fewer in number, and can be traced more or less continuously for some hundred kilometres as far as Basle. Here they either coalesce or vanish in the confusion entailed by the entry of the Rhine into an area of recent tectonic activity, the Great Rift Valley.

In considering Erb's conclusions it will be convenient to divide them into two groups ; and to treat separately :

(A). His subdivision of the Low Terrace of the Upper Rhine, and of the corresponding Young End Moraines and outwash fans of the last glacial period (Penck's Würm Glaciation) ; and

(B). His subdivision of the High Terrace of the Upper Rhine, and its associated glacial formations (Penck's Riss Glaciation).

(A). The Low Terrace

Outwash Fans of the Schaffhausen Area.

It has been recognized, at least since Hug's original paper (Hug, 1907), that the outwash fans of the Schaffhausen area are the dissected remnants of at least six distinguishable terrace surfaces, and that they, and through them their associated end moraines, can be grouped on altimetric and topographical evidence, into six successive phases. Apart from some trifling alterations in numbering, etc., Hug's original grouping forms the basis of the accepted system (Schalch, 1921 ; Schmidle, 1914 ; Erb, 1931). These glacifluvial terraces, in order of decreasing altitude and age, are as follows (fig. 3) :

Terrace I : Klettgau valley floor, and Rafzer Feld ; issuing from Enge-Neuhausen-Jestetten Moraine (maximum extension).

Terrace II : Breite Terrace ; issuing from Spiegelgut Moraine, 1.3 km. S.W. of Herblingen, and passing through the Klaffen and Wangen valleys into the Klettgau.

Terrace III ; Stockar Terrace ; issuing from Wippel Moraine S.W. of Thaingen and draining through the Fulach Valley to the mouth of the Töss and coalescing with Terrace I near Kaiserstuhl.[1]

Terrace IV : Munot Terrace ; northern drainage issuing from moraines between Thaingen and Ziegelhütte and draining through Fulach Valley ; southern drainage issuing from Lindenbuck Moraine near Feuerthalen and joining the northern branch at Schaffhausen.

Intermediate Terrace : Terrace at Altenburg, connected with a re-advance (Hug, 1907), but assigned by others to Munot Terrace.

Terrace V : Fulach Terrace ; northern drainage issuing from Gottmadingen-Bietingen Moraine ; southern drainage issuing from Altbühl Moraine near Langwiesen.

Terrace VI : Northern drainage : Upper Singen Terrace, issuing from Singen-Ramsen Moraine ; southern drainage : Schaarenwald-Rheinau Terrace, issuing from Diessenhofen Moraine.

Terrace VII : Northern drainage : Lower Singen Terrace, issuing from Arlen Moraine ; southern drainage : issuing from moraines at Etzwilen near Stein and coalescing with Lower Singen Terrace.

Low Terrace between Schaffhausen Area and Basle.

Below the Schaffhausen area, several of the gravel sheets just mentioned coalesce to form a simpler system which, by early authors, was considered a unit and called the " Low Terrace " (Du Pasquier, 1891).

Hug (1909), however, suggested that the Low Terrace was, in fact, composite, from Basle to Schaffhausen, and that, while the " Upper Low Terrace " connected with the outwash gravel sheets from the outer group of Young End moraines, the " Lower Low Terrace " ran through and connected with the outwash from the Inner Young End moraines. Hug's conclusions were generally accepted by Swiss geologists (Heim, 1919, pp. 301-302).

Kraus (1922) subdivided still further the Low Terrace in the Basle area ; but did not attempt to trace his subdivisions upstream. He called his three highest subdivisions Low Terrace V, IV and III, with surface levels at Basle of 275, 270, and 260 m., respectively. Théobald (1933), as amended by Erb (1936), confirmed the subdivision of the Low Terrace in the Basle area into a High Low, Middle Low, and Low Low Terrace.

After a careful review of the evidence briefly summarized above and a critical

[1] Hug (1907) joins the Stockar Terrace with the Klaffental (Terrace II), a connection which is unlikely because of the low position of the Stockar level at Altenburg. It is more likely that the Stockar Terrace continued down the Rhine to the mouth of the Töss as suggested in the present paper, eventually coalescing with the Rafzer Feld Terrace near Kaiserstuhl. This is, however, merely a detail, since in either case the Stockar Terrace joins the levels I and II to form the High Low Terrace of the Rhine. See p. 10.

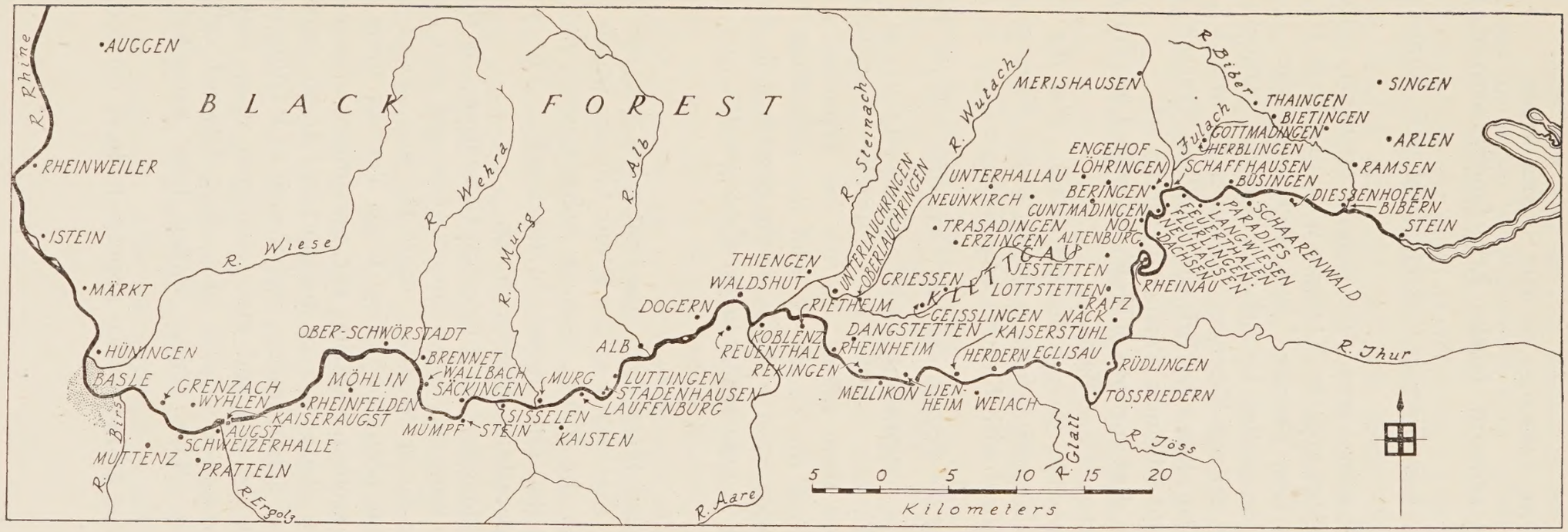

FIG. 1.

Upper Rhine from Lake Constance to Basle, with localities referred to in the text and the profile, fig. 3.

re-examination of the relevant levels, Erb (1936) arrived at the following conclusions :

(1) Hug's " Upper Low Terrace " is identical with Kraus's Low Terrace V at Basle.

(2) In the Schaffhausen area this terrace connects with the glacifluvial Stockar and Breite Terraces and the Klettgau floor (Terraces III, II, and I).

(3) Hug's " Lower Low Terrace " is, in fact, composite.

(4) Its upper portion (called by Erb the Weiach Terrace) connects with the glacifluvial Munot and Fulach Terraces (Terraces IV and V).

(5) Its lower portion (called by Erb the Mellikon Terrace) connects with the glacifluvial Schaarenwald-Rheinau Terrace (Terrace VI).

(6) It seems certain that portions of Hug's " Lower Low Terrace " are identical with Kraus's Low Terrace III at Basle.

(7) It is highly probable, though not yet certain, that the remaining portions of Hug's " Lower Low Terrace " form a single, much dissected, surface traceable to Basle and there identical with Kraus's Low Terrace IV.

The Longitudinal Profile of the Terraces and their Connection with the Terminal Moraines.

Fig. 3 represents the longitudinal profile which emerges as a result of plotting the points relied upon by Erb, together with a number of additional points derived from other authors and from maps. In the list deposited in the Institute of Archaeology are tabulated the details of, and the authorities for, each point in the profile. The methods employed are briefly described in the legend of fig. 3. They are of importance in judging the value of our results.

The Drainage Channels.

Both Erb's paper and the present one deal solely with the terminal moraines of, and drainage from, that sector of the Rhine Glacier which extended from the latitude of Thaingen in the North, through Schaffhausen and Jestetten, to that of Rüdlingen opposite the Thur mouth in the South. The westward extension of this ice front varied greatly at different times.

At its maximum extension (the " Greatest Glaciation " of the Swiss geologists) the ice front appears to have run approximately east and west, parallel to, and just north of, the Rhine, as far as Möhlin ; there the line turned south and crossed the Rhine Valley. This occurred during High Terrace times and will be dealt with in the following section. During the maximum advance of Low Terrace times (the Schaffhausen phase) the ice margin ran roughly north and south, from Thaingen, to the west of Schaffhausen, and thence to Rüdlingen, where it crossed the Rhine Valley. At the last and most restricted stage that concerns us (the Stein phase) the ice was only capable of sending forward valley lobes from the Lake Constance Basin. The Rhine Valley lobe extended as far west as Etzwilen near Stein.

West of Möhlin, the Rhine Valley appears to have carried, at all stages, the

entire drainage from the sector we are considering. East of Möhlin the situation was more complicated. The southern portion of our sector, at all times, drained down the Rhine Valley from the point at which the ice front of the moment crossed that valley. But during the Greatest Glaciation, when ice occupied the valley almost to Möhlin, lateral, marginal channels along what is now the northern flank of the valley, were also formed. Their traces are preserved as high-lying patches of gravel (most of them recorded as " stages a, b and c " in Erb, 1936). The drainage from the northern portion was still more complicated. Separate and independent drainage channels mark the successive positions of the ice front in its retreat eastward. These, during Low Terrace times, were as follows :

(1) The Klettgau, joining the Rhine at the Wutach mouth south of Thaingen (in the profile, —.—.—.—).

(2) The Wangen Valley to Griessen in the Klettgau, and thence as before.

(3) The Fulach Valley, joining the Rhine at Schaffhausen (in the profile, — — — —).

(4) West along the Biber Valley from Gottmadingen to Thaingen and thence through the Fulach Valley as before.

(5) South along the lower Biber Valley to the Rhine at Bibern.

It will be noticed that, in all cases, this northern drainage eventually reached the Rhine Valley and was therefore compelled ultimately to conform to the then existing level of the Rhine.

Description of the Low Terrace.

In the neighbourhood of Basle, four terraces can easily be distinguished within about 40 metres above the present mean water level. Two additional very low terraces have been recognized by Kraus below Basle (Kraus's I and II). They are probably floodplain levels due to the canalization of portions of the Rhine in the last century. They are not considered by Erb (1936) and are lower than our lowest terrace at Hüningen.

Falls Terrace. Our lowest terrace appears to have been disregarded by previous workers and its remains considered as post-glacial erosional steps. Although there are many such steps preserved in the Rhine Valley between Basle and Schaffhausen which cannot be combined into terraces, those included in our lowest level are highly suggestive of a definite stage in the river's history. Near Hüningen (pt. 13) this terrace is about 6 m. below the Low Low Terrace ; near Laufenburg the difference is about 10 m. (pt. 72, 73) ; and at Rheinau about 13 m. (pt. 144). No point nearer to the Falls at Neuhausen has been found, but the terrace points so clearly to the bevelled lip of the Falls that it suggests a causal connection between the two. This terrace, therefore, will be called the Falls Terrace. Its age is " post-glacial " in the sense that all the evidence indicates that the Low Low Terrace corresponds to the Stein phase of the Würm Glaciation. Whether the Falls Terrace could be due to a mere suspension of erosion during some later retreat phase seems open to question. After the retreat from Stein the load of glacifluvial

outwash would have been dropped in Lake Constance, as the river's normal load is to-day, so that an aggradation terrace from Schaffhausen to Basle could hardly have been formed. Moreover, the fact that it is in no sense a mere leaf of the Low Low Terrace and does not merge with the latter over the entire distance to Basle, certainly suggests that a considerable interval elapsed between Low Low Terrace times and its formation. Being later than the Stein phase, the Falls Terrace is not considered further in the present paper.

Low Low Terrace. At Basle, three levels of the Low Terrace can be distinguished. They are here called, Low Low, Middle Low, and High Low Terrace.

Below Basle, the Low Low Terrace is Kraus's Terrace III, as has been shown by Erb. Pt. 65, Hug's " Laufenburg-Hauenstein " point, is insufficiently located. We have placed it at Laufenburg, but the reference to Hauenstein suggests that it may well lie considerably further upstream. Pt. 77 at Alb, 4 m. above terrace level, lies in the mouth of a tributary and is therefore too high. From pt. 27 at Wylen near Basle to pt. 120 at Eglisau our Low Low Terrace is identical with Erb's Mellikon Terrace. His last point of this terrace at Rheinau, however (Erb, 1936, p. 12 ; our pt. 146), when plotted, is seen to belong to the Middle Low Terrace. Erb's statement that his Mellikon Terrace links with the Inner Young End Moraine is not, however, invalidated. A series of points (pts. 129, 139, 143, 145, 153, 156, 165, 181, 182) connect it, with a constant gradient, with a terrace at Büsingen west of Diessenhofen, whence it continues at a slightly steeper gradient into the outwash fans of the Stein phase at Arlen east of Singen. Pt. 191, 192 and 193 are parts of Erb's Terrace VII (Erb, 1931, p. 82).

Pt. 143 at Euelberg near Neu-Rheinau marks a short cut which the Low Low Terrace took here, the double meander of Rheinau being a later development. It is noteworthy that the Falls Terrace can be traced into the lower meander which, therefore, already existed when this " post-glacial " terrace constituted the flood-plain of the river. Pt. 143 is difficult to define : there is a wide expanse rising from 380 to 385 m. The latter figure is probably nearer the original terrace surface. Similarly, the narrow terrace at Nol (pt. 156) now rises from 383 to 390 m. The higher value has been taken as being probably nearer the original terrace surface.

Middle Low Terrace. Below Basle, this terrace is identical with Kraus's Terrace IV. Pts. 7 and 9, regarded by Kraus as parts of his Terrace IV, agree better in level with his Terrace V, but the general features of his system are not thereby affected. From pt. 100 at Kaiserstuhl to pt. 127 at Tössriedern, our Middle Low Terrace is Erb's Weiach Terrace which he (Erb, 1936, p. 11) suspected of being identical with Kraus's Terrace IV and of being independent of both the Mellikon and High Low Terraces. The profile suggests that in this he was correct.

The Middle Low Terrace is about 10 m. above the Low Low Terrace at Basle. They converge downstream so that at Rheinweiler the difference has shrunk to 2 m. Above Basle, the difference remains about 12 m., but rises to 16 m. at Eglisau Railway Bridge.

Above Eglisau, the Middle Low Terrace sub-divides into a lower and upper

leaf, both of which emanate from terminal moraines. The lower leaf is the Schaarenwald Terrace of Hug (1907 ; not considered by Erb, 1936), which is the sandr of the Diessenhofen terminal moraine. This sandr (pts. 197, 185, 184, 183) connects smoothly with a number of points in the neighbourhood of the Falls (pts. 166, 158, 154, 149). Although this was unknown to Hug, his views on this terrace were correct, since he regarded it as passing through pt. 146 at Rheinau. A continuation of the gradient indicated by these points takes one to pt. 127 at Tössriedern, and thus into the Middle Low Terrace.

The upper leaf of the Middle Low Terrace is known as the Fulach Terrace. Its continuity with the Weiach Terrace was established by Erb (1936, p. 12 ; but note misprint in line 2, where *Stockarterrasse* should read *Fulachterrasse*). In the Rhine Valley this terrace emanates from the terminal moraine of Langwiesen-Altbühl ; in the Fulach Valley, from the Gottmadingen Moraine near Bietingen.

While the continuity of the Schaarenwald and the Fulach leaves with the Weiach or Middle Low Terrace is evident, the relation of the next higher leaf, the Munot Terrace, remains doubtful. Erb (1936, p. 11) considers that this terrace converges into the Middle Low Terrace, forming its highest leaf. An analysis of the conditions at Altenburg reveals that the Munot Terrace can as readily be continued into the High Low Terrace, of which it would form the lowest leaf. Erb's Munot Terrace points are, in our profile, pts. 160, 172, 175 and 186. The lowest of these (pt. 160) is at Neuhausen and a continuation of the existing gradient would, as suggested by Erb, bring the Munot level down to the Middle Low Terrace near pt. 127 at Tössriedern. Terrace remains at Lottstetten (pt. 141) and Rüdlingen (pts. 134, 133), however, suggest a continuation of the Munot Terrace at a lesser gradient roughly parallel to, and about 8-10 m. above, the Fulach Terrace, with the probability of its joining the High Low Terrace below Eglisau. In our profile, the Munot level has not been continued beyond pt. 133 and the question therefore left open.

There is, however, some indication that both interpretations of the Munot Terrace may, in fact, be true. Just below pt. 160 (Erb's last Munot Terrace point) a conspicuous terrace surface extends southward, west of Nol, to the neighbourhood of Altenburg (pts. 159, 157, 151). Its gradient is steeper than that of the upper continuation of the Munot Terrace through pts. 141, 134, 133, and it strongly suggests that at some time after the upper level was formed, a " trumpet " (Troll, 1926) was cut into the Munot surface, running down to the Fulach level. Now this is the terrace (Hug, 1907) we called on p. 4 the " Intermediate Terrace ". It has no equivalent downstream or upstream. Hug correlated it with a re-advance of the ice which, after Munot times, deposited morainic material on the gravels of the Stockar and Munot terraces. In short, the Munot Terrace would originally have formed the lowest leaf of the High Low Terrace. After a recession of the ice, during which the river eroded to the bench of the Middle Low Terrace, a re-advance would have brought the ice on to the Munot gravels and the meltwater

would have created the ramp from the Munot level down to that of the Middle Low Terrace.

High Low Terrace. Below Basle, the High Low Terrace is identical with Kraus's Terrace V. About 10 points determine the High Low Terrace between Basle and Eglisau. Thence it is continued by its lowest leaf, the Stockar Terrace. A higher leaf branches off between Kaiserstuhl and Eglisau and rises to the terminal moraine at Nack. This leaf is known as the Rafzer Feld. It was formed during the most westerly stand which the ice reached during the Last Glaciation. This stage is also the oldest. In order to avoid overcrowding the profile, we have omitted the Rafzer Feld. Instead, we show the great northern branch of the drainage system, that through the Klettgau (see p. 10).

So far as we know, the Stockar Terrace has been studied only above the mouth of the Thur (pts. 135, 142, 152, 170, 180 : all on Erb's authority). It begins in the Fulach Valley at the Kreuzgut near Herblingen. Its connection with the High Low Terrace was established indirectly by Erb (1936, p. 11) ; for he showed that it cannot be connected with his Weiach Terrace at Tössriedern (pt. 127), since the gradient of the hypothetical connection would be too steep. In fact, pt. 130 at the mouth of the Töss is the link between pts. 112, 116, 119 and 123 of the High Low Terrace near Eglisau, and pts. 132, 135, 128 and 137 of the Stockar Terrace opposite the Thur mouth. Point 130 is one of Weber's points (Weber, 1928). The Stockar Terrace at this stage, therefore, followed the course of the present Rhine from the Thur mouth south to the Töss mouth and thence in a north-westerly direction to Eglisau.

In addition, there exists a short cut at the Stockar level due west from the group of points opposite the Thur mouth (pts. 132, 135, 128, 137) to the upper Schwanen Valley at Eglisau (pts. 125, 126). Thence, with a greatly increased gradient, the terrace drops to pts. 122 and 119 at Eglisau, that is to the level of the High Low Terrace. The sudden increase in gradient between pt. 119 and 125 suggests that there was retrogressive erosion from the level of the High Low Terrace up to the upper Stockar level, but that it was arrested at an early stage. The cause may have been that a similar process of retrogressive erosion northwards from the present mouth of the Töss had succeeded in cutting back more rapidly, thus draining the water into the channel which from that time to the present day has been in permanent use. Even the gradient of the lower Stockar level appears to be slightly irregular. This may indicate that the Stockar Terrace represents a comparatively short phase in the history of the Rhine. Only the Munot level, if extended over the 10 km.-gap from the mouth of the Thur to that of the Glatt, would form an evenly graded continuation of the profile of the High Low Terrace above Eglisau.

The Breite Terrace is a very high leaf of the High Low Terrace formed after the Rafzer Feld but before the Stockar Terrace (pts. 148, 155, 161, 164, 168, 176). It is said to have drained through the Wangen Valley into the Klettgau (Hug, 1907).

The Klettgau. The valley of the Klettgau begins just west of Neuhausen and runs westwards, roughly parallel to the Rhine, until it joins the Wutach from the Black Forest and debouches into the Rhine at Koblenz opposite the mouth of the Aare. It is treated independently in the profile, for it provides a valuable check on the Rhine terraces. The Klettgau carried the meltwater of the Rhine Glacier only during the maximum phase of the Last Glaciation.[1] It carried the northern drainage during the same period in which the Rafzer Feld carried the southern drainage.

The Breite Terrace, or at any rate the drainage through the Wangental, joined that through the lower Klettgau below Griessen. At this stage, very little water was present in the Klettgau above its junction with the Wangental, a mere trickle compared with the glacifluvial stream of the preceding stage. The lack of a stream capable of efficient erosion has characterized the Klettgau ever since.

Each successive lowering of the Rhine, however, initiated a knickpoint which, by retrogressive erosion, cut back up the Wutach and, to a progressively lesser extent, up the Klettgau. The surface knickpoints are clearly preserved, and each marks the junction of a terrace with the present floodplain. In them we have corroborative, and in a sense independent, evidence for the successive stages in the history of the Rhine. In following the floodplain one notices five knickpoints at pts. 217, 222, 224, 228, and 237.

In the Neunkirch district, there is a remarkable bulge in the profile. The valley bottom from Guntmadingen (pt. 247) to Brühl, 1.5 km. E. of Neunkirch (pt. 244), is horizontal, while from there to about 1 km. below Neunkirch it gives the appearance of having been raised by local aggradation. This fact is not apparent from Hug's figures for the gradient of the Klettgau floor (Hug, 1907, p. 57), for he took long stretches of the valley thus smoothing out the above feature as well as the knickpoints. But Du Pasquier, as early as 1891 (p. 18), recognized that the valley floor above Guntmadingen and below Neunkirch, if connected by a straight line, would represent the curve of an ordinary valley floor. This is of course the level of the glacifluvial Klettgau phase. The Neunkirch bulge was considered by Du Pasquier to be the deltaic cone of the Seltenbach. The most natural explanation of this bulge is probably to regard it, as Du Pasquier did, as a detrital cone deposited during a subsequent phase, or phases, of aggradation. But it looks as if the Ergoltingerthal as well as the Seltenbach contributed to the aggradation.

All three Low Terraces of the Rhine are represented in the lower Wutach and the lower Klettgau. The Falls Terrace reveals its youthfulness by the fact that it has only just reached the Klettgau. As shown in the profile, they join the floodplain of the Wutach-Klettgau system successively at the following points : The Falls Terrace at pt. 217, the Low Low Terrace at pt. 222, the Middle Low Terrace at pt. 224, the Breite level of the High Low Terrace at pt. 228, and the " Klettgau valley leaf " floor of the High Low Terrace at pt. 237. While the

[1] For Penultimate Glaciation, see p. 14.

lower terraces are each evidenced by at least three points in addition to the knickpoint, the two levels of the High Low Terrace are continued below the knickpoint by only two points and one point, respectively. Even if these three points were unknown, however, both levels have gradients which, if prolonged downstream, join the High Low Terrace near the mouth of the Klettgau. This confirms Hug's view that the upper Klettgau and the subsequent Breite stage constitute the two oldest leaves of the High Low Terrace in this area.

The Significance of the Longitudinal Profile of the Low Terraces.

An inspection of our profile reveals that it fully substantiates Erb's major conclusions. In addition it affords further evidence for his belief that both portions of Hug's " Lower Low Terrace " can be traced as independent surfaces as far west as Basle, where they coincide with Kraus's Terraces III and IV.

It further reveals, however, that the levels when plotted appear to require two minor modifications of Erb's scheme and to suggest the possibility of a third modification :

(1) Contrary to what Erb assumed, but did not attempt to prove (Erb, 1936, p. 12), it seems difficult to believe that the Schaarenwald-Rheinau Terrace is confluent with the Low Low Terrace. Instead it appears to merge naturally into the Middle Low Terrace, thus forming the lowest leaf of the group of glacifluvial gravel trains that coalesce to form that terrace (Erb's Weiach Terrace).

(2) The true glacifluvial continuation of the Low Low Terrace appears to be an even lower terrace than the Schaarenwald-Rheinau level. It is in fact Terrace VII (the lower Singen Terrace) which Erb, as a result of his field work north-east of Schaffhausen, found it necessary to add to the six previously recognized terraces (Erb, 1931, p. 82). In the Rhine Valley, Terrace VII, in so far as noted by previous workers at all, appears to have been dismissed as " postglacial " (Schalch, 1921, at Lottstetten ; Schmidle, 1914 ; Heim, 1919, pp. 277 et seq., pl. xiii ; Heim, 1931, pp. 43-44). In fig. 3 we have plotted Erb's Lower Singen Terrace of the northern drainage sector, instead of its Rhine Valley equivalent, because the remnants of the former are better preserved in the Biber Valley than are those of the latter between Bibern and the southern sector of the ice front at Stein.

(3) The third point has already been discussed on p. 9. We there suggest that the Munot Terrace, as originally aggraded, formed the lowest leaf of the High Low Terrace ; that after a recession of the ice and erosion to the bench of the Middle Low Terrace, a re-advance brought the ice on to the Munot gravels and that its outwash then created the ramp from the Munot level down to that of the Middle Low Terrace. If this suggestion is correct, the actual sequence of events was more complicated than that postulated by Erb ; for he regarded the Munot Terrace simply as a leaf of the Middle Low Terrace. He thus omitted the whole of its history prior to its short final phase. It should be noted that Hug's evidence for a re-advance finds support in Erb's discovery of interstadial sands at Bietingen. They are immediately overlain by the ice-deposits of the Bietingen-Gottmadingen

phase which drained through the Fulach Valley (Erb, 1931, p. 69 ; Erb, 1936, p. 13). Erb himself considers these sands an argument in favour of an interstadial break prior to the Middle Low Terrace.

Last Glaciation, Summary.

If the major conclusions arrived at by Erb and the modifications suggested by us are sound, we seem justified in picturing the course of events in our area during Penck's Würm Glaciation somewhat as follows :

(1) A maximum ice advance reaching across the Rhine to the upper end of the Klettgau, followed by a retreat during which the ice successively abandoned the Neuhausen, Spiegelgut-Herblingen, Kreuzgut-Herblingen and Lindenbuck-Feuerthalen moraines.

(2) An interstadial of sufficient magnitude and duration to permit fluviatile erosion (to at least as far downstream as Basle), from the surface of the High Low Terrace to the bench of the Middle Low Terrace. Two at least of the conditions necessary for such erosion would have been : a period of time many times as long as that between the successive glacifluvial leaves representing retreat stadia ; and sufficient climatic amelioration to put an end to valley-side solifluction, climatic aggradation and glacial outwash, which must previously have inhibited all fluviatile erosion. It is important to note that the differences in altitude now observable between the three sub-divisions of the Low Terrace represent a part, perhaps only a small fraction, of the total erosion that took place. Our levels are, of necessity, only surface levels, and we have no knowledge whatever of how deeply interstadial erosion had cut, before the ensuing glacial aggradation heaped up the terraces whose dissected surfaces are all that is now visible.

(3) A re-advance of the ice, which stopped short of the maximum of (1) *supra*, but possibly extended at some points to beyond the moraines of the Stockar and Munot phases. The first two stages of the subsequent retreat are marked by the Langwiesen-Altbühl and Diessenhofen moraines.

(4) An interstadial comparable in magnitude and duration to (2) *supra*, during which the Rhine eroded its bed from the surface level of the Middle Low Terrace to that of the bench of the Low Low Terrace.

(5) A re-advance of the ice to, but not beyond, the lobate front of the Arlen-Stein Moraines ; followed presumably by further " post-glacial " stadia corresponding to " Ammersee, Bühl ", etc.

Thus, in the Rhine area, the Last Glaciation of the Alps can be sub-divided into three phases of ice advance separated by two interstadials, the first advance having been the greatest, and the third, the smallest.

(B) The High Terrace

The High Terrace Profile.

The points inserted in the profile of the High Terrace do not represent the whole of the known evidence. We have made use of as many as possible of the

relatively low-lying points that have been attributed to the High Terrace by various authors. Those recorded High Terrace points that lie above the two levels here considered have been with a few exceptions omitted.

In the region of Basle it seems certain that recent tectonic movements have warped and dislocated all levels above the High Low Terrace. For this reason the many points referred to by Gutzwiller (1895, 1912) have been omitted, and no High Terrace points below the Möhliner Feld have been used.

Low High Terrace. The lowest level of the High Terrace is represented by a number of points assigned by Erb to his level " c_2 ", together with a number added from other sources. Most of Erb's level " d " points appear, when plotted, to belong to the High Low Terrace. A group of three points (pts. 55, 58, 61) between Säckingen and Laufenburg is succeeded upstream by a gap as far as Reuenthal opposite Waldshut (pt. 194). Thereafter, many points extend up the Wutach and the Klettgau, ending at Enge at a point 500 m. above sea-level. The southern branch of this level, if one existed, has not been traced.

In the Klettgau, there is a suggestion of an upper leaf to the Low High Terrace (pts. 223, 235, 246) which possibly begins at Enge at 522 m. and merges with the lower leaf in the neighbourhood of Thaingen. These two leaves of the Low High Terrace stand in much the same relation to one another as do the leaves of the three sub-divisions of the Low Terrace. They probably represent retreat stages of one and the same glacial phase.

In the Klettgau the Low High Terrace lies about 10 m. above the top leaf of the High Low Terrace and, apart from slight variations, maintains this relative altitude at least as far west as the Möhliner Feld.

Upper High Terrace. The term " Upper High Terrace " is here applied to the line connecting a number of points which maintain a constant gradient nearly parallel to the High Low Terrace from Laufenburg up the Rhine to the Buchberg near Rüdlingen. A northern branch runs up the Klettgau. The latter, however, cannot be traced further than pt. 230 near Erzingen. The connection with pt. 234 indicated in the profile is tentative.

This level is the next lowest level above the Low High Terrace that can be reconstructed from High Terrace points. The result, when plotted, appears reasonably consistent. The fact that there appear to be no remains of intermediate levels between the Low High Terrace and the Upper High Terrace, strengthens the argument that the latter constitutes a genuine terrace surface. It includes three important points from Heim's High Terrace (Heim, 1919) ; also several points of Erb's level " c_2 ".

The Upper High Terrace lies between 15 and 18 m. above the Low High Terrace near the Wutach mouth. Downstream it diverges slightly, reaching 25 m. above the Low High Terrace near Laufenburg.

High Terrace Points above the Upper High Terrace. Numerous points at a higher altitude than the two levels just described have been assigned by various authors to the High Terrace. A few instances have been inserted in the profile to indicate

the sort of altitude at which they occur. Erb distinguishes three high levels (a, b, c_1), of which he considers that the lowest coalesces with his yet lower level c_2. He regards a and b as older and as representing two leaves of the maximum advance of the Riss Glacier. As will appéar later, we have been unable to accept this view in its entirety.

" *The Greatest Glaciation.*" *Historical Review.*

There is strong evidence for the conformable connection of the Low High Terrace with the moraines of the " Greatest Glaciation ". In the terminology of earlier writers, who recognized only one High Terrace (the bulk of which corresponded to our Upper High Terrace), this fact was expressed by the statement that moraines, older than the Last Glaciation, occur at levels much lower than the surface of the High Terrace.

Mühlberg (1896) was the first to advance this view and since, like everyone else at that time, he regarded the High Terrace (in the traditional sense) as a glacifluvial aggradation surface, he drew the logical conclusion that an additional glaciation must have intervened between the High Terrace Glaciation and the Last Glaciation. Moreover, the moraines of this intermediate glaciation showed it to have been the most extensive ice-sheet ever formed over Switzerland. He therefore called it the " Greatest Glaciation ".

Mühlberg's views inevitably raised difficulties for Brückner (Penck and Brückner, 1909) when he attempted to apply Penck's fourfold system to the Rhine Valley. He tried to dispose of Mühlberg's extra glaciation, which according to the latter intervened between Riss and Würm, by suggesting that the High Terrace gravel was deposited during a halt in the advance of the Riss Glacier ; and that the moraines of the Greatest Glaciation represented the subsequent maximum advance. Because of the low altitude at which moraines of the Greatest Glaciation occur, this necessitated the assumption of considerable erosion into the High Terrace gravels by the ice of the Greatest Glaciation. Nevertheless, Penck and Brückner's interpretation was widely accepted.

Objections were, however, soon raised. Blösch (1911) contended that Penck and Brückner's view was untenable because both erosion and weathering proved that the High Terrace and the Greatest Glaciation were separated by a very considerable time interval. Some of this evidence will be discussed later.

Heim (1919) when writing his " Geology of Switzerland " found himself in a difficulty. His purpose, throughout this truly monumental work, was primarily to compile a record of established facts. Yet, with the facts in question, it was impossible to avoid discussing Mühlberg's " Greatest Glaciation ".

Heim does not expressly accept Mühlberg's scheme of five glaciations (Heim, 1919, p. 274). But he comes extremely near to doing so in fact. He repeatedly emphasizes, by italics and by bold-faced type, that Mühlberg had conclusively established his major point : that the Greatest Glaciation in Switzerland

was demonstrably later than the period of the aggradation of the High Terrace.[1]

Heim then undertakes to reconcile this fact with the fourfold Penck-Brückner system, by minimizing the glacial character of the High Terrace. He says (p. 275) that the issue is whether the formation of the High Terrace is to be attributed to a glacial or an interglacial period. He states that, while the High Terrace (our Upper High Terrace) was being aggraded, the ice margin lay as far back as the Alpine valleys ; and suggests that it is, therefore, largely a question of definition whether or not such a phase should be regarded as a *Glazial*. If one considers it a *Glazial*, Mühlberg's scheme of five glaciations would be valid ; if one considers it merely an oscillation during the interglacial that preceded the Greatest Glaciation, there the fourfold system of Penck and Brückner could be maintained. Heim (1919, p. 275) inclines to the second alternative. His table (p. 343) shows that in his own view the Greatest Glaciation corresponds to Riss, while the High Terrace Glaciation ranks merely an episode during the Great Interglacial. It also shows that in Penck and Brückner's view the Greatest Glaciation constitutes the latter part of Riss while the High Terrace Glaciation constitutes the earlier part.

In short, therefore, Heim was satisfied that, following the glaciation of the Lower Deckenschotter (Mindel), there occurred :

(*a*) an interglacial,

(*b*) the aggradation of the High Terrace as outwash of a relatively small glacial phase,

(*c*) an interglacial,

(*d*) the Greatest Glaciation,

(*e*) the Last Interglacial,

(*f*) the Last Glaciation with its various phases.

The essential difference between Brückner and Heim is that the former regards (*b*) as an advance phase of (*d*) and minimizes (*c*) ; while Heim on the whole favours the view that (*a*) and (*c*) constituted a single interglacial and that (*b*) was of relatively small magnitude.

The High Terrace Glaciation.

In recent years fresh evidence has confirmed the correctness of the above sequence and has given us additional data as to the extent of the High Terrace Glaciation. Hug (1932) describes such evidence from the Lake Zürich area, inside the Würm moraines. The section at Seebach, for instance (Hug, 1932 ; profile and further discussion in Beck 1933, p. 357, fig. 4) is as follows :

(5) About 2 m. boulder clay, loamy. Würm Glaciation.

(4) About 10 m. gravel, cemented, intensively weathered and with glacial polish on top.

[1] This attitude of the great Swiss geologist is certainly an argument in favour of the conclusions reached by Mühlberg, Blösch, and others ; and of those based on somewhat different evidence, expressed in the present paper.

(3) 1 m. loamy moraine with scratched erratics.
(2) 19 m. gravel, partly cemented (known from borings only).
(1) 12 m. muddy beds with very few pebbles (known from borings only).

According to Hug, the gravel (4) originally passed upwards into the moraine of the Greatest Glaciation, the evidence for this lying outside the Würm area. Weathering and cementation of (4) took place during the Last Interglacial and the ice of the Last Glaciation removed the upper portion of (4). Thus, the succession of events would have been as follows :

(*a*) After Mindel, deep erosion of valleys and the formation of mud deposit (1) due to damming.

(*b*) Deposition of gravel (2) while glaciers lay inside the Glatt Valley and Wädenswil.

(*c*) Advance of a glacier into the Glatt Valley and towards Zürich, depositing moraine (3).

(*d*) Retreat of the glacier into the Alps, upper gravel (4) deposited.

(*e*) Advance of the glacier beyond the limits of Würm : Greatest Glaciation.

(*f*) Last Interglacial, weathering and cementation of (4).

(*g*) Last Glaciation, removal of upper part of (4).

This evidence, and Hug's interpretation of it were discussed by Beck (1933, 1937) who found similar conditions in the Aare Valley near Bern. He named the advance responsible for deposit (3) of the Seebach section, the " Glütsch Glaciation". Beck goes even further than Hug in that he regards the mud beds (1) as also morainic (his " Kander Glaciation ") ; a contention which still requires confirmation.

From Hug's and Beck's evidence it seems probable that the glacial phase which preceded the Greatest Glaciation had at least as wide an extension as the third Würm phase (Zürich-Stein phase) and that in the valleys of the fore-hills of the Alps, the moraines of this phase are covered by gravel, partly interglacial or interstadial (Beck, 1933, p. 358), and partly the advance outwash of the Greatest Glaciation.

If the Buchberg section near Eglisau is correctly assigned to the Upper High Terrace (Heim, 1919, p. 294), the ice of the Glütsch Glaciation must have reached about as far as the Schaffhausen phase of the Würm Glaciation, for here the terrace gravel is said to pass into morainic material (Du Pasquier, 1891, p. 43). Hug agrees with Du Pasquier on this point ; but Heim (1919, p. 275) considers it possible that older morainic material was incorporated in a younger gravel (see also p. 20, *infra*).

The most probable explanation, therefore, of the High Terrace is that :

(*a*) Inside the area of the Zürich-Stein phase (with which the Glütsch phase probably coincided approximately in extent) the Upper High Terrace consists of advance gravels of the Glütsch phase, the Glütsch moraine and, on top (interstadial or interglacial gravels and) advance gravels and moraine of the Greatest Glaciation.

(*b*) Outside this area, the Upper High Terrace consists solely of outwash

gravel of the Glütsch phase, while moraines of the Greatest Glaciation cover it unconformably and extend down to a later terrace which is separated from the Upper High Terrace by an erosional interval. Another erosional interval separated this lower terrace from the entire Low Terrace complex.

Middle Terrace.

The Greatest Glaciation has already been linked by some with such an intermediate terrace, called by them the " Middle Terrace ". It was traced by Steinmann (1893) and Tschudi (1904) from the Möhliner Feld into the Rhine Rift Valley north of Basle ; but Erb (1936) has shown that in the Rhine Rift the deposits should be interpreted as tectonically disturbed portions of the Low Terrace. Erb also denies the existence of a " Middle Terrace " above Basle.

In the area near Basle, the Middle Terrace found a protagonist in Gutzwiller (1912). But this area, too, has been subjected to tectonic disturbances. As many of the points that have been referred to the " Middle Terrace " appear unreliable, it seems best to follow Erb in abandoning the term. But as will appear shortly, several former " Middle Terrace " points are included by us in our Low High Terrace.

Moreover, even though we discard the term " Middle Terrace ", we must bear in mind that Steinmann and Du Pasquier (1893) claimed that the Penultimate Glaciation consisted of two phases, the later of which they linked with the " Middle Terrace ". Schmidle also (1911) distinguished six gravel terraces near Thiengen, two of which he considered separate phases of the High Terrace. Heim (1919, p. 299) makes essentially the same suggestion as Steinmann and Du Pasquier, adding that the " Middle Terrace " is perhaps connected with the Greatest Glaciation. At the same time Heim, following Mühlberg, warns us that we must not expect to find inside Switzerland continuous glacifluvial gravel terraces of the Greatest Glaciation, since the entire country was covered by ice during the maximum of that glaciation.

Finally, Weber (1928) distinguished in the valleys of the Töss and Glatt a High Terrace and a " Middle Terrace ".

The Connection of the Low High Terrace with Moraines of the Greatest Glaciation.

As Heim pointed out, the great extension of the Greatest Glaciation renders it unlikely that traces of its sandr belt are to be found in Switzerland. It is nevertheless possible that such traces may be preserved further north in Baden. Erb (1936) has described numerous localities of this kind at an altitude far above our Upper High Terrace and, for the most part, belonging to his levels a and b. He found (1936, p. 28) that a chain of dammed lakes was formed by the ice of the Greatest Glaciation. The ice crossed the interglacial drainage of the Rhine Valley almost at right angles and blocked the valleys leading down from the Black Forest. The high-lying gravels of the High Terrace complex (i.e. those above our Upper High Terrace) are apparently contemporaneous with the maximum of the Greatest Glaciation.

This raises the crucial question : what was the level of the Rhine when it was reached by the advancing ice of the Greatest Glaciation ? Erb holds the view that it was approximately at the height of his levels a and b ; and that his lower levels c_1 and c_2 represent a re-advance after a retreat from the maximum extension ; represent, that is, a later and smaller glacial episode. Such an interpretation is possible ; but only if we are prepared to accept the extremely steep gradient at which his levels descend into the Rhine valley in the neighbourhood of the Möhliner Feld. Fortunately there is no need to postulate such extraordinary gradients, since our profile reveals two terraces (the Low High Terrace and the Upper High Terrace) which run essentially parallel to the present river as far downstream as the Möhliner Feld area. This suggests that the Rhine, before it was overwhelmed by the advancing ice of the Greatest Glaciation, may have been flowing far below Erb's a and b levels, and at that of either the Upper High, or the Low High, Terrace.

As between these alternatives, the evidence adduced by Mühlberg, Blösch, Heim and others for extra-alpine low-level morainic deposits indicate that it was the Low High Terrace that was overwhelmed by the ice of the Greatest Glaciation.

Evidence for this can be found within our area :

(1) Pt. 204, west of Thiengen, is described by Erb (1936, p. 27) as gravel conformably connected with " end moraine material with abundant large erratics ". This point, one of Erb's c_2 points, lies without question on our Low High Terrace.

(2) Pt. 194, south of Reuenthal, is described by Blösch (1911, p. 30) as an irregularly bedded gravel with scratched erratics. It is regarded by him as part of a transition cone of the Greatest Glaciation. This point, too, lies precisely on our Low High Terrace.

(3) In the area of the Möhliner Feld, the extreme moraines of the Greatest Glaciation cross the Rhine in a north-south direction. Two terminal moraines have been described here, as well as ground-moraine. In a profile given by Heim (1919, pl. xii, fig. 7) the moraine is clearly shown descending from the level of his High Terrace (350 m.) to about 335 m. Our Upper High Terrace, if prolonged at constant gradient, would have an altitude of approximately 350 m. at the Möhliner Feld ; while our Low High Terrace, if similarly prolonged, would lie at about 325 m., i.e. only some 10 m. below the moraine shown in Heim's section. This section is, for several reasons, so significant that it has been omitted from the profile with regret. Heim unfortunately fails to give the data necessary to determine its horizontal position with sufficient accuracy.

In addition to the above, a number of points, beginning with Erb's at the mouth of the Wehra (pt. 44), and all lying below the level of the Upper High Terrace, if prolonged, suggest the presence there of a transitional, or sandr, cone descending to the level of the Low High Terrace (pts. 38, 37, 34).

The conformable connection of the Greatest Glaciation with the Low High Terrace seems therefore probable. It may be objected that at a few places morainic material has been reported *below* the level of the Low High Terrace and even as

low as the Low Terrace complex. If this is true, it is conceivable that Brückner's suggestion that the glacier eroded locally to below the gravel floor of the valley, provides the explanation. In fact, however, only two points of this kind have been recorded from the Rhine Valley. Upon examination they appear more readily explicable along different lines.

One of these points is at Schäffigen near Laufenburg, which Blösch (1911, p. 31) considered important. The supposed moraine consists overwhelmingly of Black Forest material and chunks of cemented gravel ; not of the Alpine and Molasse material that would have been deposited by a glacier advancing from Switzerland. Indeed it is impossible to visualize how an Alpine glacier could have obtained this Black Forest material. As the locality is on the southern slopes of the Black Forest, it seems probable that the Schäffigen " moraine " is in reality a solifluction deposit. When Blösch wrote his monograph, solifluction had not yet been recognized as an important phenomenon. His failure to discriminate between the two methods of deposition is therefore not surprising.

The second point is described by Erb (1936, p. 29). It lies between Murg and Laufenburg " on the road N. of spot-level 335.1 m." The topographical sheets of Baden have not been accessible for study, but we have been unable to identify this point on the Swiss map which, for the territory of Baden, is based on the Baden survey. It is described by Erb between two others at 373.5 m. and 375.9 m. ; all three being assigned by Erb, without comment, to his c_1 level. Since no figure as low as 335 m. appears on Erb's own map, but only figures of 380 m. and 352 m., and since he does not discuss the exceptionally low altitude of this point, it is not impossible that a printer's error may have substituted 335 m. for 385 m., or some similar figure.

The Upper High Terrace and Its Relation to Moraines.

Heim (1919) believes that the Upper High Terrace, in so far as it lies outside the extension of what is now called the Glütsch phase, is not conformably connected with moraines. The only locality within our area where the Upper High Terrace is said to pass into moraine, is the Buchberg near Eglisau (see p. 28). The genuineness of this connection has been contested by Heim. Further, since morainic deposits of the Greatest Glaciation are known to descend as low as the Low High Terrace and to ascend the slopes to above the level of the Upper High Terrace, patches of moraine and outwash gravel may occur at any height between these limits. Their occasional presence, therefore, at the level of the Upper High Terrace has no special significance. Many of Erb's High Terrace remains, especially those with a gradient steeper than the Rhine terraces, appear to belong to this class. They may well have been formed in the earlier stages of the retreat of the ice from its maximum.

On the other hand, any exposure of Upper High Terrace gravel, *if weathered* and covered *unconformably* by moraine, would indicate that the Upper High Terrace was separated from the Greatest Glaciation by a period of ice recession and mild

climate. Heim (1919) holds the view that such a period did intervene. Moreover, Mühlberg originally separated the Greatest Glaciation from the Upper High Terrace gravel, largely because in some exposures near Aarau he observed that weathering and cementation of the High Terrace had taken place before the moraine of the Greatest Glaciation was deposited upon it (Mühlberg, 1896). These observations are supported by Blösch (1911).

Unfortunately, in the Rhine Valley, no such section has been described, to our knowledge. Judging, however, by Heim's profile of the Reuenthal area (Heim, 1919, pl. xii, fig. 5) and Du Pasquier's (1891) description, there appears to be a discordance between moraine and Upper High Terrace gravel at this spot.

Thus, the High Terrace complex of the Upper Rhine, that corresponds to the Riss Glaciation, appears to be divisible into : (1) an earlier and smaller glacial phase (approximately of the size of Würm III) with the Upper High Terrace as its glacifluvial level ; and (2) (after a period of mild climate with erosion and chemical weathering) the Greatest Glaciation of Switzerland, with the Low High Terrace as one of its glacifluvial levels.

SUMMARY OF THE DEVELOPMENT OF THE RHINE TERRACES

The longitudinal profile of the Rhine terraces, together with the evidence of numerous geological sections, indicate that the terraces of the Rhine in the area studied developed in the following manner :

(1) After the Mindel Glaciation (Lower Deckenschotter), i.e. during the Great Interglacial, the valleys were eroded to a level far below the level of the present rivers.

(2) A period of aggradation followed (the *Rinnenschotter* of Swiss geologists) which filled the furrows. This ended with, or was followed by, a glacifluvial aggradation emanating from an ice-sheet which in this area was of approximately the same size as that of the third phase of the Last Glaciation. This is Beck's Glütsch phase and the glacifluvial terrace aggraded by it is the Upper High Terrace of the present paper.

(3) The Glütsch phase was followed by a period of valley erosion and chemical weathering, i.e. by an interstadial or interglacial period.

(4*a*) The subsequent advance of the ice-sheet of the Greatest Glaciation produced a further aggradation. In the Alpine valleys and in the foreland as far as Lake Zürich, this aggradation raised the thalweg to such an extent that the gravels and the moraine of the Glütsch phase were covered by the later glacifluvial gravel. On the surface of the latter the glacier advanced and deposited a moraine. A complete section in this inner area, therefore, would consist of two gravels enclosing the Glütsch moraine and covered by the moraine of the Greatest Glaciation.

(4*b*) In the peripheral areas, such as the Rhine Valley, the initial aggradation did not rise above the Upper High Terrace, but produced a separate and lower gravel surface, the Low High Terrace. Subsequently, the ice of the Greatest Glaciation therefore deposited on the surface of the Low High Terrace outwash mingled with moraine.

(4*c*) Since the ice of the Greatest Glaciation was thick enough to cover the slopes of the valleys high above the Upper High Terrace, and since in the Rhine area it moved across the Rhine Valley on to the southern slopes of the Black Forest, patches of glacifluvial outwash and moraine were plastered on to the hillsides at levels well above the Upper and Low High Terraces. Many Lakes were also dammed up locally, but their drainage made its way westward to reach the level of the Low High Terrace west of the Möhliner Feld. The gradient of this drainage system was therefore steeper than that of the river terraces (Erb's phases a, b, and possibly c_1).

(4*d*) During the retreat of the Greatest Glaciation from its maximum many

new drainage systems of this type came into existence temporarily and in rapid succession. All, however, drained to the pre-Greatest Glaciation level of the Low High Terrace, wherever this had become ice-free. It is possible that a phase, or halt, can be recognized in this retreat as claimed by Erb (his level c_2). This is also suggested by the upper leaf of the Low High Terrace in the Klettgau.

(5) After the recession of the Greatest Glaciation, interglacial erosion was resumed, and the Rhine cut down to form the bench of the High Low Terrace. For this erosion the entire Last Interglacial was available. Such long-continued erosion naturally attached most actively the lowest of the terraces then existing, with the result that no remnants of the Low High Terrace are preserved over long stretches of the river's course in the peripheral area.

(6) The Last Glaciation opened with an advance (never afterwards exceeded) to the Neuhausen-Jestetten moraine. The corresponding glacifluvial aggradation is the Klettgau leaf of the High Low Terrace. During the retreat from the maximum three further stages can be distinguished. In the Schaffhausen area, they are represented by the Breite, Stockar and Munot leaves.

(7) During the ensuing interstadial, the Rhine eroded the formations of the preceding period to form a new bench, now hidden beneath the gravels of the Middle Low Terrace.

(8) The second advance of the Last Glaciation may have begun with a push extending nearly to the limits of the first phase (Hug's re-advance). The intermediate terrace at Altenburg, sloping down to the Fulach level may be its glacifluvial equivalent. This stage was short-lived. It was followed by two distinct retreat stages, represented by the Fulach and the Schaarenwald leaves of the Middle Low Terrace.

(9) During the second interstadial of the Last Glaciation, the Rhine cut through the gravels of the Middle Low Terrace to form a new bench, now hidden below the gravels of the Low Low Terrace.

(10) The third advance of the Last Glaciation brought the ice to the Etzwilen-Arlen moraine, usually called the Stein phase. Its glacifluvial outwash forms the Low Low Terrace.

(11) After the retreat of the ice, erosion was resumed over the whole course of the Rhine to Basle, but at some period during the course of Post-glacial times the Falls Terrace was formed. This event was apparently connected with the development of the Rhine Falls at Schaffhausen.

Part II

THE AGE OF THE MAGDALENIAN

Climatic phases of the Last Glaciation in the Schaffhausen District

The evidence described in Part I of this paper shows that the glaciation which supplied the glacifluvial outwash that built up the " Low Terrace " of the Rhine, was composed of three glacial phases of comparable magnitude (though the second was slightly smaller than the first, and the third smaller than the second). These glacial phases are separated by interstadials of sufficient duration and magnitude for the Rhine to have eroded its bed from Schaffhausen at least as far downstream as Basle, a distance of some 120 kilometres, to a depth of certainly not less than ten metres. The erosion was actually from one glacifluvial surface to the bench of the next lower terrace. The benches being now covered with gravel are inaccessible to study. The figure of 10 metres is therefore a bare minimum, since it merely represents the vertical difference between the terrace surfaces.

Now, the " Low Terrace " of the Rhine between Schaffhausen and Basle is one of the numerous " Low Terraces " of the valleys of the Alpine Foreland, the whole of whose deposition represents, by original definition, Penck's *Würm Glaciation.* One is entitled, therefore, to call the three glacial phases of this complex established in the Schaffhausen area, Würm I, Würm II and Würm III.

The maximum advance of Würm I is marked by the Neuhausen-Jestetten moraine. It was followed by three retreat stadia (see p. 13).

Würm II was probably smaller than the maximum of Würm I ; though the second and third of the retreat stages of Würm I appear to have been over-ridden. The first and largest advance of Würm II appears to have covered with morainic débris the lower leaves of the glacifluvial terrace of Würm I, i.e. the High Low Terrace, without the formation of a terminal moraine. Two retreat stages of Würm II, however, left terminal moraines with glacifluvial terraces issuing from them. These are (1) the Langwiesen-Altbühl moraine in the Rhine valley and the Gottmadingen moraine in the Fulach valley, with the Fulach leaf of the Middle Low Terrace issuing from the latter ; and (2) the Diessenhofen moraine, with the Schaarenwald leaf of the Middle Low Terrace issuing from it. These stages help to date the Magdalenian sites of the area.

Würm III, finally, only overlapped the rim of the Lake Constance basin in the relatively low areas of the outlets. Down them it sent lobes. The maximum extension of these is marked by the recurved moraine of Stein and Singen (Etzwilen-Arlen). Thereafter the ice withdrew, and stages of its retreat are marked by a series of moraines on the edge of the lake basin, and presumably by others *inside*

the periphery of the Alps. Whether any of these stadia mark a re-advance of the ice (as opposed to a mere halt) cannot be decided from the evidence available in the Lake Constance area.

Position of the Magdalenian in the sequence of Climatic Phases

Magdalenian sites. There are three sites in the area of Lake Constance and Schaffhausen, which are rich both in fauna and industrial remains: the Schweizersbild, the Kesslerloch, and the Petersfels. The two former are on Swiss territory, the last in Baden. All three have been correlated with the system of glacifluvial terraces of the Lake Constance area.

Schweizersbild. The deposits of this rockshelter (Nüesch, 1896) rest on gravels of the Breite Terrace which was formed during the first retreat stage of Würm I (see p. 10, and the longitudinal profile). The moraine of this stage lies only 600 metres south-east of the site. On the glacifluvial gravel issuing from this moraine there lies, in the Schweizersbild section, 1.5 metres of local limestone gravel, deposited by a stream after the ice had retreated from the moraine. This gravel in turn is covered by a " coombe rock " or limestone breccia which possibly indicates frost-weathering (Penck, 1902, p. 308). It was only after the formation of this breccia that Magdalenian man settled at the Schweizersbild.

It seems clear, therefore, that a long hiatus exists between the formation of the Breite Terrace and the occupation of the Schweizersbild. How long it was, cannot be determined by geological evidence. Penck (1896, p. 176) also came to this conclusion. Most authors at present incline to regard this station as comparatively late; basing their view either on the absence of certain species from the fauna, or on the typology of the bone industry. Thus, the late Magdalenian of the Schweizersbild is certainly considerably later than the Breite Terrace stage of Würm I, while the character of the fauna precludes a date later than Würm III. The fauna suggests Würm II, interstadial Würm II/III, or Würm III and, if one takes seriously the absence of the mammoth and the woolly rhinoceros[1], a late date within these limits. Late Würm II (as suggested in Zeuner, 1945, p. 267) is therefore unlikely.

The uncertainty involved in the palaeontological argument, especially since it is based on the *absence* of certain species, renders the Schweizersbild less important from the chronological point of view than the two remaining sites.

Kesslerloch. The Kesslerloch cave (Nüesch, 1904; Heierli, 1907) lies in the Fulach valley close to its northern end at Thaingen. Down this valley (in addition to terraces referable to Würm I) runs the Fulach Terrace. It originates in the Gottmadingen moraine several kilometres upstream from the Kesslerloch. Downstream it merges with the *Middle* Low Terrace of Würm II age.

The cave is so situated that it would have been uninhabitable so long as the

[1] This species was originally recorded as *possibly* present, but the only evidence was a piece of a rib. Stehlin regarded the species as absent. See Soergel, 1919, p. 153.

glacifluvial stream poured down the valley. The habitation can date, at the earliest, from the time when the glacifluvial river ceased to flow, i.e. after the

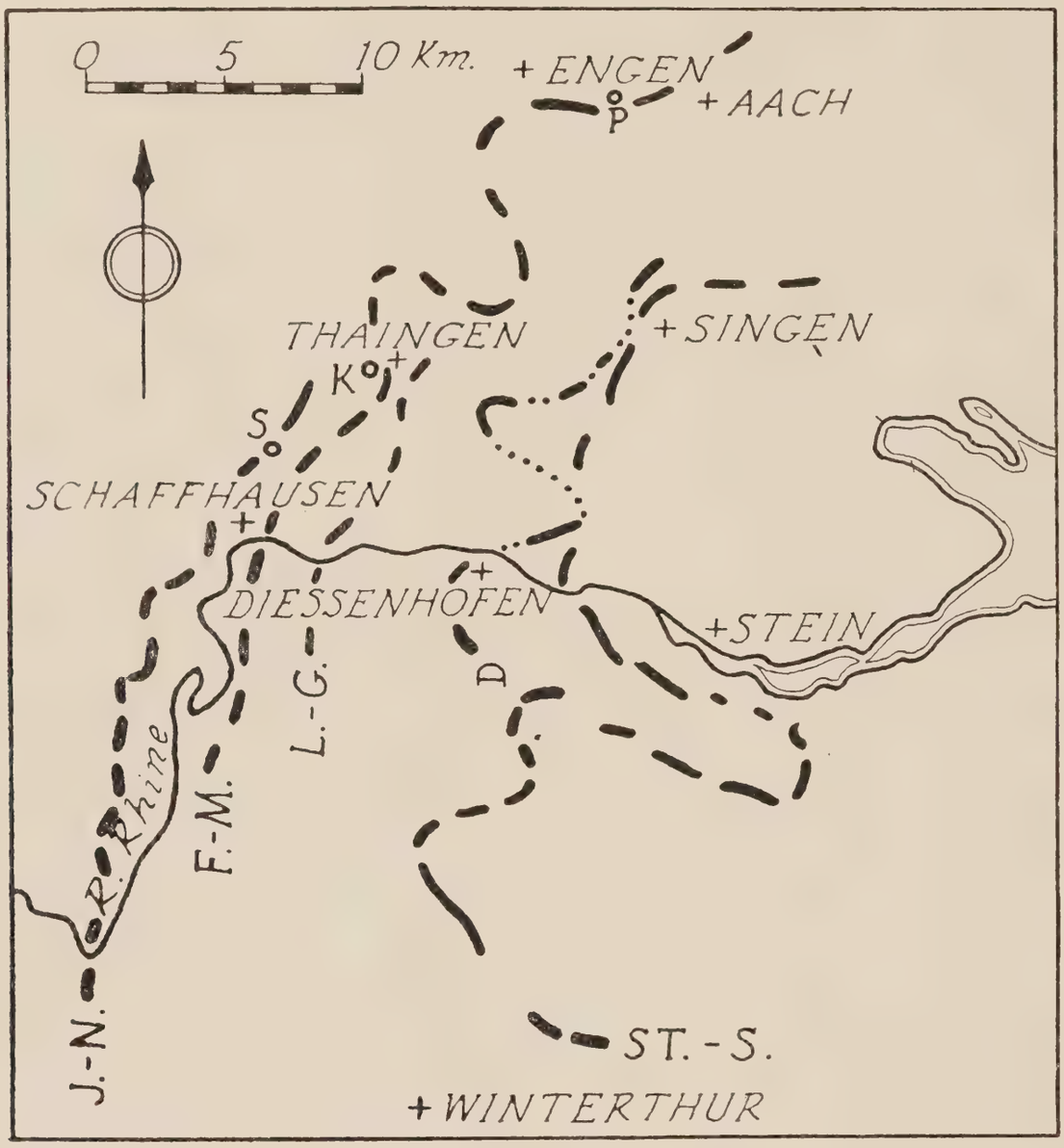

Fig. 2.

Approximate run of the moraines of the Last Glaciation in the Schaffhausen area, and position of Magdalenian sites. J.-N. Jestetten-Neuhausen moraine (Würm I). F.-M. Feuerthalen (Lindenbuck)-Munot moraine (Würm I). L.-G. Langwiesen (Altbühl)-Gottmadingen moraine (Würm II). D. Diessenhofen moraine (Würm II). ST.-S. Stein-Singen moraine (Würm III). S. Schweizersbild. K. Kesslerloch. P. Petersfels.

ice had begun to retreat. The basal deposit of the valley is a glacifluvial gravel (Meister, in Heierli, 1907, p. 51) which passes upwards into sand and, finally, loam. A decreasing discharge is thus clearly indicated. The yellow loam is best interpreted as a floodloam. It was during the formation of

its earlier portion that Magdalenian man occupied the cave (Meister, l.c., pp. 55-56).[1]

Clearly floodloam formation and occupation of the cave can have been contemporaneous. It is common knowledge that the floodplains of modern rivers, on which loams are deposited during floods, are dry and inhabitable during most of the year. The simultaneous formation of the detrital cone in the cave and the floodloam outside, which Meister (in Heierli, 1907, p. 55) considers an established fact, is indeed probable, and it is unlikely that Magdalenian man would have been deterred by occasional seasonal floods from using an otherwise suitable cave.

The geological evidence, then, apparently tells us that the earliest Magdalenian from the Kesslerloch must date from *after* the maximum of Würm II. It does *not* tell us, however, how long after Würm II we should set this date. Nor does it tell us how long the cave was occupied ; for floodloam formation appears to have continued into the Postglacial. But the fauna enables one to fix the chronological position of the occupation.

The sub-division of the fauna and of the archaeological objects according to their levels were insufficiently emphasized by the excavators ; but Heierli in his summary (1907, p. 211 ff.) did point out differences both in fauna and industry. Soergel (1919, p. 154) made it clear that the three major levels distinguished by Heierli, which correspond roughly to the early, middle and late Magdalenian (R. R. Schmidt, 1912, p. 72), differed in their contained faunas :

The lowest level (Heierli's III) contained among other species the woolly rhinoceros and musk-ox, with mammoth and reindeer at their maximum frequency. Soergel (1919, p. 154) regards its fauna as pronouncedly glacial.

The middle level (Heierli's II) lacked woolly rhinoceros and musk-ox, but contained the forest forms, beaver and roe-deer.

In the upper level (Heierli's I) the disappearance of the forest forms, beaver and roe-deer, indicates a return of cold conditions ; the glacial character of the fauna is again more pronounced (Soergel, 1919, p. 155). On typological grounds, the Schweizersbild has been equated with this layer, both being considered late Magdalenian ; and there also the fauna was thought by Nüesch to indicate a phase of " arctic climate ".

The faunal succession, therefore, suggested to Soergel (1919) that the climate was still very cold when early Magdalenian man appeared at the Kesslerloch,

[1] Now, during the withdrawal of the ice, an event appears to have taken place which affected greatly the local hydrography. As the ice withdrew east, the river Biber came into existence, discharging to the south-east into the Rhine. Presumably it did not take long for this new river to cut back into the Gottmadingen moraine, to breech it and eventually, after gnawing backward across the sandr of this moraine to reach the Fulach. At a point almost facing the Kesslerloch cave, the headwaters of the Fulach were thus captured by the Biber and carried south-east, instead of flowing south-west through the Fulach valley. The Fulach itself was reduced to the small stream it now is. This reversal of drainage appears to have been established before Würm III times ; for the Fulach valley contains no terrace later than the Fulach Terrace of Würm II age. The drainage of the Stein-Singen (Würm III) stage was directly west along the Rhine, the Biber being one of its tributaries. The reversal of drainage between the Gottmadingen moraine and the Kesslerloch would not have prevented further accumulation of floodloam, though the present position of the river suggests that it was drawn away from the cave, which thus was made more habitable by the reduction of the risk of flooding. F.E.Z.

and that the middle Magdalenian corresponded to a slightly milder phase with at least some forest growth, which phase was presumably the interstadial Würm II/III. The advent of Würm III was marked, or heralded, by the disappearance of the forest elements in the upper layers, which contain the *late* Magdalenian.

Petersfels. Further very suggestive evidence is to be found at the Petersfels near Engen, some 15 kilometres north-east of the Kesslerloch (Peters, 1930 ; Peters & Toepfer, 1932 ; Zeuner, 1945, p. 76, p. 268 ; 1946, p. 161). This Magdalenian rockshelter lies on the extreme margin of the Würm I ice. It was inhabited for a shorter period, for here the industry as a whole is considered middle to late Magdalenian. Garrod (1938, p. 9) compares it with the French Magdalenian IV, V and VI. The Magdalenian layers rest on a heavy solifluction deposit of " coombe rock " type, itself covered by a weathering loam 15-20 cm. thick. They are overlain by another solifluction deposit of the same type. The Magdalenian occupation, therefore, was preceded by a cold phase, and a phase mild enough to produce chemical weathering ; and was followed by another cold phase. It seems, therefore, fairly closely dated to the end of an interstadial and/or the early part of the next glacial phase.

The entire succession lies in a valley which, according to Toepfer and earlier workers, was excavated by glacifluvial water from the moraines of Würm I, and Toepfer concludes that the lower solifluction represents Würm II, and the upper, Würm III. The possibility that the Petersfels Magdalenian belongs in the interstadial Würm I/II cannot be said to be disproved by the geology, because the basal solifluction may have followed immediately upon the formation of the glacifluvial valley. But, archaeologically, it seems highly improbable : for we do know that the typologically older Magdalenian of the Kesslerloch cannot have begun until after the Würm II maximum.

If, on the other hand, we equate the two coombe-rocks with Würm III and some *later* phase, the section contains nothing to represent the Würm II maximum. Yet the ice front then stood closer than at any subsequent time. Such a correlation, furthermore, assumes a relatively warm weathering period followed by a substantial re-advance of the ice in post-Würm III times, for which we have no evidence. The remaining alternative is that proposed by Toepfer : to correlate the two coombe-rocks with Würm II and Würm III, and to regard the late Magdalenian occupation as dating from the end of the interstadial Würm II/III.

To summarize : The Kesslerloch tells us that its Magdalenian cannot be earlier than the beginning of the retreat of Würm II. How long it lasted cannot be established with certainty, though there are indications that it persisted there until the climate had once more deteriorated markedly. The Petersfels evidence strongly suggests that the late Magdalenian occurred between the end of interstadial Würm II/Würm III and the maximum of Würm III. Here no evidence is available for the beginning of the Magdalenian. The two sites together appear to give us a bracket that restricts the maximum possible duration to a period that stretches from sometime in the last half of Würm II to sometime in the first half of Würm III.

Absolute Chronology of the Magdalenian

Two criticisms have been levelled at the chronology here proposed. The first is purely typological. It asserts that the Magdalenian forms too homogeneous an industry to have passed through climatic fluctuations that involved marked changes in the environment. It should be noted, however, that the climate of Europe during the second interstadial of the Last Glaciation was by no means mild and temperate.[1] The general character of its fauna rather suggests that, though tundra and steppes were in many localities replaced by forests, the climate was more like that of the northern forests of Europe and Canada, which are regularly visited by reindeer on their seasonal migrations. Since the Magdalenian was an industry essentially based on the exploitation of the reindeer, no marked change in the economy of Magdalenian man would have been affected.

The second criticism concerns the consequences which it is thought would follow from an application of the absolute chronology. By that chronology, Alpine Würm II is dated at the summer radiation minimum of c. 72,000 years ago, and Würm III at that of c. 25,000 years ago.[2] Hence it is said that if the relative chronology outlined by us is correct, the Magdalenian must have persisted for some 50,000 years (see Zeuner, 1946, p. 290). This, it is true, is inherently improbable. For apparently the final Levalloisian and Mousterian, the Chatelperronian, Aurignacian *s.s.*, Western Gravettian and Solutrian occupied in all something less than 50,000 years, i.e. from the climax of the first phase of the Last Glaciation (radiation minimum 115,000) to that of the second (radiation minimum 72,000).

Now it is true that on the evidence at present available the only satisfactory correlation appears to be to equate the three phases of the Würm Glaciation of the Alps with the three radiation minima referred to above. It is also true that the period between the last two radiation minima amounts to approximately 50,000 years. But to say, as we have maintained above, that the Magdalenian appears to have begun and ended in a cold phase and to have spanned the entire interstadial Würm II/Würm III is by no means to assert that the Magdalenian persisted from 72,000 to 25,000 years ago.

All the evidence we possess as to the second interstadial of the Last Glaciation (not only that from the Würm Glaciation of the Alps, but that derived from the Weichsel Glaciation of northern Europe and from the sea-level of this interstadial, see Zeuner, 1945, p. 35, p. 133) indicates that the climatic amelioration was relatively small ; small that is, not merely as compared with a true interglacial but even as compared with the preceding interstadial. As to the duration of this slight improvement we as yet know nothing. *Prima facie* it seems possible that an

[1] See further as to this our suggested answer to the second criticism.

[2] To date them thus is, of course, to disregard the inevitable " lag " or " retardation " between climatic minimum and maximum glaciation. But we are forced to do this for of the magnitude of this " lag " we know as yet next to nothing. The argument, however, remains unaffected provided one assumes that in each case the amount of " lag " was of the same order of magnitude.

interstadial which the palaeontological evidence shows to have been weak, may well have been short. In other words the Kesslerloch evidence appears to tell us that Magdalenian man entered into occupation while cold conditions still persisted, but this—so far as we know—may have been 10, or even 20,000 years *after* the minimum of summer radiation of 72,000 years ago. Similarly (though this is perhaps less likely) the climatic deterioration that almost certainly set in before Magdalenian man disappeared from the scene, may have occurred thousands of years prior to the radiation minimum of 25,000 years ago. It may well be that the cold did not attain its maximum severity until 25,000 years ago, or even later ; but faunistically the evidence for an interstadial depends on the appearance and disappearance of forest elements. At what precise date the cold became sufficiently severe to eliminate these elements, we are completely ignorant.

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Fig. 3. Longitudinal profile of terrace surfaces between Lake Constance and Basle.

Numbers refer to list of points deposited in the Institute of Archaeology. The numbering runs upstream, at each locality proceeding from the lower to the higher terraces. Apparent slight geographical displacements downstream or upstream are due to the inevitable compression or lengthening of the profiles of the terraces relative to the profile of the present river.

The base-line of the profile is the course of the present river (middle-water level), with its meanders. It is slightly shortened in some places in order to avoid breaks in the gradients of the terraces. The floodplain could not be used since it comprises several minor terraces in some places and is absent in others.

The " points " selected for the profile have been critically examined, and no reasonable doubt could be entertained regarding their correctness. They were taken from a number of publications quoted in our bibliography, from the geological maps and the Swiss Siegfried Atlas. Heights are given in metres, and the values used by the respective authors and those found on maps were used without modification. Actually, the Baden (Geological Survey) and Switzerland (Siegfried Atlas) sheets 1/25,000 refer to different " Ordnance Data " both of which have been corrected in recent years (Heim, 1931, p. 3 ; Erb, 1936, p. 6). The correction has, however, been applied to very few sheets only, and it has been found impossible to ascertain the exact character of the corrections. Discrepancies may amount to two or three metres. To avoid them as much as possible, the Swiss Siegfried Atlas has on the whole been used, since on it the contours have been made continuous across the frontiers, though spot heights were apparently left uncorrected. In spite of this difficulty the terrace system constructed exhibits reasonable and consistent gradients.

Rhine Valley : ————————

Klettgau branch :—·—·—·—·—

Fulach Valley : — — — —

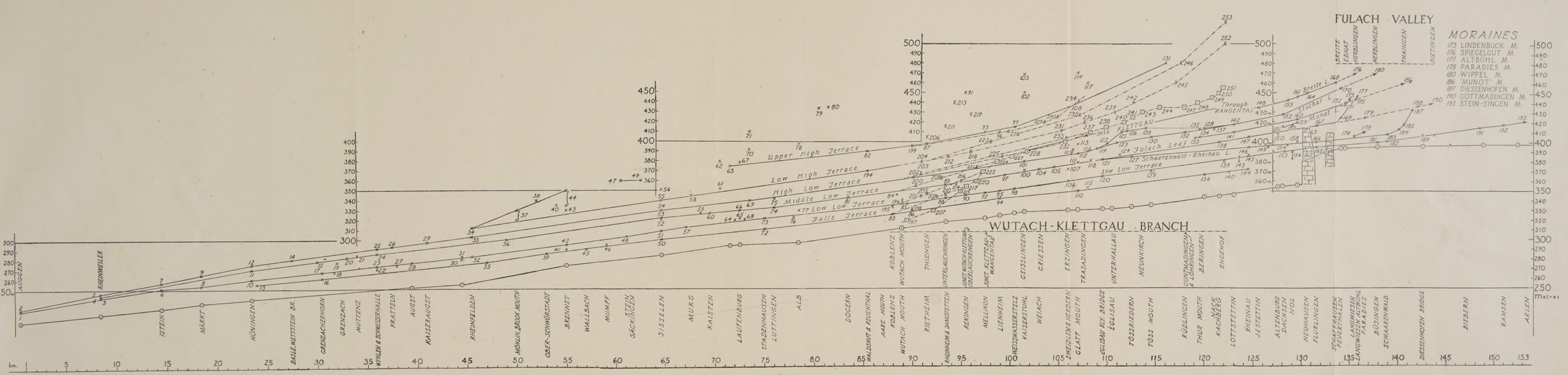
FULACH VALLEY
MORAINES
173 LINDENBUCK M.
176 SPIEGELGUT M.
177 ALTBÜHL M.
178 PARADIES M.
180 WIPPEL M.
186 MUNOT M.
187 DIESSENHOFEN M.
190 GOTTMADINGEN M.
193 STEIN-SINGEN M.
WUTACH-KLETTGAU BRANCH
Upper High Terrace
Low High Terrace
High Low Terrace
Middle Low Terrace
Low Low Terrace
Falls Terrace
Fulach Leaf
Low Low Terrace
Through WANGENTAL
KLETTGAU
Metres
km.

Fig. 3.

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